Advanced Communication and Networking Technologies for Mars Exploration

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Abstract–Next-generation Mars communications networks will provide communications and navigation services to a wide variety of Mars science vehicles including: spacecraft that are arriving at Mars, spacecraft that are entering and descending in the Mars atmosphere, scientific orbiter spacecraft, spacecraft that return Mars samples to Earth, landers, rovers, aerobots, airplanes, and sensing pods. In the current architecture plans, the communication services will be provided using capabilities deployed on the science vehicles as well as dedicated communication satellites that will together make up the Mars network. This network will evolve as additional vehicles arrive, depart or end their useful missions. Cost savings and increased reliability will result from the ability to share communication services between missions.

This paper discusses the basic architecture that is needed to support the Mars Communications Network part of NASA's Space Science Enterprise (SSE) communications architecture. The network may use various networking technologies such as those employed in the terrestrial Internet, as well as special purpose deep-space protocols to move data and commands autonomously between vehicles at disparate Mars vicinity sites (on the surface or in near-Mars space) and between Mars vehicles and earthbound users. The architecture of the spacecraft on-board local communications is being reconsidered in light of these new networking requirements. The trend towards increasingly autonomous operation of the spacecraft is aimed at reducing the dependence on resource scheduling provided by Earth-based operators and increasing system fault tolerance. However, these benefits will result in increased communication and software development requirements. As a result, the envisioned Mars communications infrastructure requires both hardware and protocol technology advancements. This paper will describe a number of the critical technology needs and some of the ongoing research activities.

1. Introduction

Future Mars exploration will be supported by a multiplicity of in situ intercommunicating entities that require the ability to share information among themselves and with the Earth users. There will be multiple active missions, producing ever-increasing amounts of scientific data and many of these missions will also need a significant amount of local communication (e.g., teams of rovers). The aggregate data produced by these missions will be multiplexed through a backbone network to the Earth that will eventually support data rates in the Gigabit per second range. This is a substantial increase over the current capabilities. , The current Mars Global Surveyor mission is representative of the state-of-the-practice in Mars-to-Earth telecommunications and utilizes direct links to Earth based on X-band microwave communication link technologies at data rates up to approximately 85 kilobits per second. Clearly, new technologies will need to be brought to bear to achieve this increased capacity and to support the new in situ networking. The Mars communication architecture will be designed to evolve in such a way as to meet anticipated near term (2001-2010), mid-term (2010-2020), and far-term (beyond 2020) requirements. The architecture itself will be defined in terms of several types of communication subnetworks, called architectural elements[3], and specific technology developments are described in the context of these elements. These architectural elements for the Mars network are defined below:

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[3] In [1], a different architectural decomposition was defined. However, in the interest of having a common set of terms with the Mars communication activities, we use the nomenclature of the Mars program for this paper.

A. Mars-Earth backbone network – This architectural element provides the long haul data links directly between Mars vehicles and the Earth as well as the Earth-based infrastructure elements. The remote assets include elements with long-haul capabilities (certain Mars surface vehicles, spacecraft in Mars orbit) and the in-space data relay network. The Earth-ground segments include the deep space network (DSN), NASA and other space agency Intranets and virtual private networks (VPN's), and the Internet. The critical technologies involve increasing the capacity and the autonomous operation of the remote long haul space link assets.

B. Mars vehicle proximity networks – These involve the wireless links with distances that are relatively near to the planet. There are three types of proximity links.

   1. Orbiter to/from Surface (called access network in [1]): This architectural element provides the data links between Mars surface/airborne vehicles and spacecraft in Mars orbit. The orbiters will typically contain the long haul links to Earth and will host a gateway to the backbone network to relay between the backbone elements and the mission spacecraft and/or vehicles, or will forward to another proximity vehicle.
   2. Mars inter-spacecraft networks - This architectural element provides the data link between spacecraft flying in formation, clusters, or constellations in the Mars vicinity. It also includes the communication interfaces between approaching/departing spacecraft. In particular, spacecraft in a communication constellation that intercommunicate to relay the data to Earth are included.
   3. Mars surface networks (called proximity network in [1]): This architectural element provides the data links between surface vehicles (rovers, airplanes, aerobots, landers, and sensors) spread out in an ad hoc network.

C. Local area networks (LAN's) on-board the Mars vehicles (included in the access network [1]): This architectural element interconnects the various modules of the vehicle through an internal LAN consisting of one or more types of serial or parallel interconnected busses.

The choice of protocol suites for use in the Mars Network is critical as this is the first true deep space-based "network" [2]. Standardization of the protocol interfaces facilitates the use of familiar terrestrial software constructs that provide transparency and hide the details of the communication architecture. There is a powerful incentive to provide transparency as this reduces software development costs and increases software reliability. Where possible, Internet protocol (IP)-compliant services can be used to enable the use of powerful Internet-like applications (ftp, e-mail), application program interfaces (sockets), and languages (Java, Java Script, HTML, XML, etc.) that simplify the task of coding operations that move data and command and coordinate activities between Mars vehicles. However, due to differences between terrestrial environments and those at planetary distances, several important services that are unique to the deep space-based environment are desired. Examples of these services include accommodation of long propagation delay times, handling periodic link outages efficiently, providing intermediate-node data custody, best-effort delivery of data with portions missing and noted, and non-blocking function operation. Applications built on top of these services may need to be explicitly modified from their terrestrial counterparts. The benefits derivable from maintaining an open communications architecture (such as the Internet) will help to achieve the long lifetime of the Mars networks and the need to accommodate missions planned over the next 10 to 30 years. In the long term, these issues are being examined in the context of the Interplanetary Internet (IPN) where the Mars network represents a subnetwork within the larger space network [3].

Protocol layering can be used to support this transparency while providing the ability to include customized services within a well-defined reference model. There are two basic design questions that must be considered. These are 1) what services and interfaces are presented to the application layer software developers, and 2) what protocols are used to implement the services at each layer. As an example of the former, an application programmer interface (API) that is identical to sockets may be provided, but the underlying protocols may be specially tailored to the space links. As an example of

the latter, with proper layering, one could easily replace a standard IP routing protocol (e.g., Bellman-Ford) with a non-internet routing protocol (such as an ad hoc routing scheme), with no application layer changes. The choice to use a non-standard protocol at a given layer may be warranted by specific aspects of the environment such as power efficiency, or to provide a service that is not available in any existing protocol. In recognition of the fact that there is not a unique protocol suite that provides the best solution for each architectural element, there is a need to define the interfaces between the selected protocols and to develop gateways that will perform translations while maintaining transparency.

A heterogeneous collection of spacecraft is anticipated to be deployed and their internal architectures can range from fully distributed to fully integrated to accommodate the specific requirements of the vehicle's mission. Many Mars vehicles will implement on-board, Local Area Networks (LAN's) to route data and commands between subsystems and science instruments. Standards are emerging that define common interfaces for the on-board communication needs. Integration with the general Mars communication architecture through common protocols that provide standard naming and addressing schemes will permit simplified access to resources (e.g., instruments) by users and other vehicles.

The Mars network will eventually provide both scheduled and on-demand service to users and vehicles. The eventual operational concept for the Mars network is that it will enable the user to control his/her vehicle (or instrument) or the vehicle to move its data to Earth without explicit scheduling by ground personnel, thereby reducing overall mission operations costs. The Earth-side support of the Mars network is basically the maintenance of the Earth-Mars backbone link and its connection to the Earth-side space agency intranets and ultimately the Internet. Eventually the data that traverses the backbone will be self-routing, wherein the destination addresses in the data packets find the end-point user or space vehicle applications. The mission operations group need not concern itself with packet routing.

As the interest in Mars exploration grows and new vehicles are deployed with more and better communications assets, the architecture will acquire greater capabilities. In sections 2-4, we describe the potential near-term (out to 2010), mid-term (out to 2020) and far-term (beyond 2020) scenarios for the Mars network. Then in section 5 we discuss new technologies that address the requirements that we foresee in terms of the architectural elements.

2. Mars Near-Term Communication Architecture

The near-term architecture for the Mars communication infrastructure is illustrated in Figure 1. This architecture provides moderately high-speed communication between Earth and Mars vehicles via the radio frequency (X-, Ka-band) equipment incorporated on each scientific orbiter sent to Mars as well as on-board the large rovers. Each of these orbiting vehicles incorporates a moderately high data rate RF backbone link to the Earth-based DSN as well as a moderate data rate proximity link to other Mars surface vehicles. Many of the orbiters will also provide navigation information to the surface elements. In addition, the infrastructure will be augmented by a dedicated communications satellite (ASI Telesat) to be put in place to perform data relay functions for surface vehicles, such as the Scout-class that do not have the ability to communicate directly to Earth. As shown in the figure, low rate proximity networks will be employed between Mars vehicles, such as between landers and rovers as necessary. Missions using intercommunicating
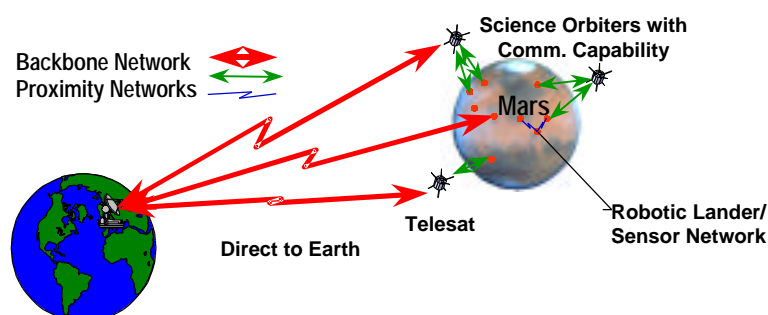
Figure 1. Mars Near-Term Communication Architecture

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sensor pods are possible, but not yet planned.

3. Mars Mid-Term Communication Architecture

The mid-term architecture for the Mars communication infrastructure is illustrated in Figure 2 and includes the Robotic Outpost, representing the first permanent presence on Mars. Sensor networks will be used to monitor the local environment around the outpost. This architecture provides high-speed communication between Earth and Mars vehicles via a micro-satellite constellation designed specifically for Mars communications and navigation purposes [4]. Each of these spacecraft incorpo-
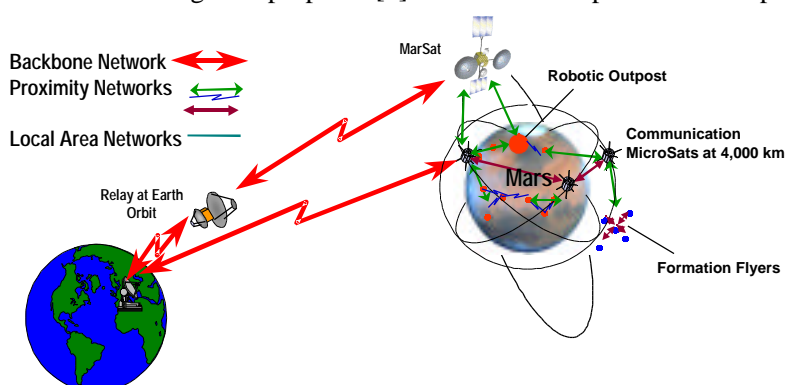
rates a high data rate Ka-band package for the backbone connection to the Earth-based DSN as well as high data rate access links to Mars vehicles. One or more Mars communications satellites (MarSat) will be placed in Areosynchronous Mars Orbit (AMO) and used to provide continuous coverage for the Microsats and ground vehicles in view. It will support the

Figure 2. Mars Mid-Term Communication Architecture

high-rate communications to/from Earth. This MarSat would become an always available, high-speed link for the Robotic Outpost below it. In addition, there is likely to be one or more Earth orbiting relay stations that operates using high-speed RF or optical means to provide additional DSN capacity and availability.

4. Mars Far-Term Communication Architecture

The far-term architecture for the Mars communication infrastructure will be used in support of Human Exploration and Development of Space (HEDS) missions and is illustrated in Figure 3. This archi-tecture provides high availability, high-speed communication between Earth and the Mars Base and other Mars vehicles. The traffic patterns will drastically shift from the predominantly data-to-earth requirement to a high volume of two-way traffic, consisting of a wide variety of types (e.g., voice, video, data) to/from Earth to support the human presence. There will also be an increased need for

local communications to handle the human gener-ated local traffic. At this point in time, the Mars network will become the most important hub of the Interplanetary Internet and handle data from other deep space mis-sions. In order to support communications at all times, relay stations placed at gravitationally stable Lagrangian points associated with the sun and the Earth may be em-
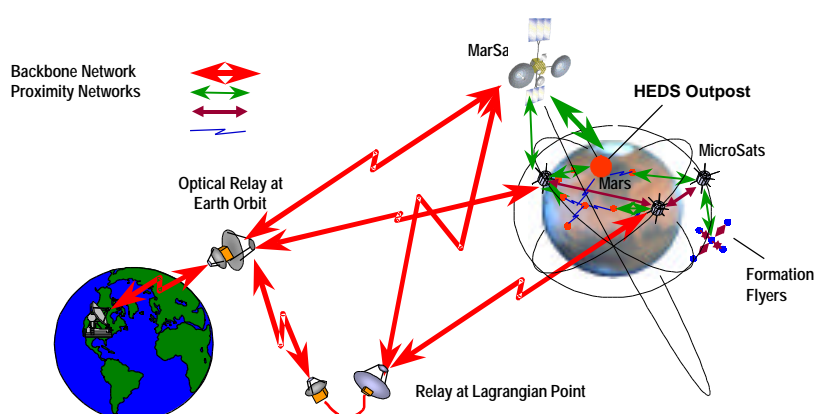
Figure 3. Mars Far-Term Communication Architecture

ployed to avoid blackouts during the periods that the sun is between Earth and Mars. These relay stations will also be backbone elements of the intra-solar system IPN communications network. Each of these relay stations may incorporate high data rate microwave and optical packages for the intra-backbone communications links. Multiple Mars communications satellites (MarSat) in Areosynchronous Mars Orbit (AMO) will be used to handle the high data rate communications link from other communication assets and ground vehicles to Earth either directly or via the relay network. They will be the primary high availability, high-speed relay links for the manned Mars stations and expeditions below.

5. Description of technologies by architectural element

Below we describe key communication and networking technologies for the backbone, proximity, and spacecraft bus architectural elements.

Technologies for backbone networks

Technologies for the Mars backbone networks need to focus on delivering higher data rates at very long distances and also address the transport layer protocols issues for such distances. The use of Ka band technologies will allow increase in data rates currently achievable at X-band frequencies. In the long term various methods of employing optical communications will be the next step to increase the data rates.

At the physical layer, the backbone technologies that are under development address increasing the data communications rate on several fronts. For use in the near term, the technologies will increase the radiated power output of Ka-band transmitters, improve the sensitivity of receivers, and handle higher rate digital bit-streams. These technologies include: 1) high efficiency Ka-band 30W and 100W traveling wave tube amplifiers (TWTA's), 2) ultra low noise cooled receivers, 3) high-efficiency Ka-Band MHEMT MMIC solid state amplifiers, 4) high rate modem circuits, 5) efficient optical power sources, and 6) micro-radian acquisition and tracking technologies.

The current state-of-the-art for 32 GHz TWTA's is the 20 W amplifier on the Cassini spacecraft. Its efficiency of ~ 40% represented a doubling of what had been achieved up to that time. Developing space-qualified amplifiers producing greater than 200 W of RF power will require the use of a different type of circuit than used in the lower power amplifiers. Previously the development of a dramatically different amplifier would require several iterations before producing an amplifier that met the desired performance. However, recently the number of required iterations has been drastically reduced due to greatly improved computer modeling capability. New development in high quality heterostructural materials will allow production of hi-efficiency Ka-Band MHEMT MMICs amplifiers with 0.1 micron device structure to operate at more than 50% efficiency.

Figure 4. Laser Communication Telescope

Critical optical technologies, such as the laser telescope in Figure 4, are also being developed that promise large gains in signal to noise ratios.

Simulation and optimization of the TWT designs, Figure 5, are being pursued to increase power, efficiency, reliability, and data transmission rate for TWT amplifiers while reducing design time and cost.
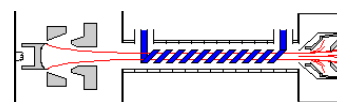
Figure 5. TWT schematic

The physical layer backbone technologies that are intended for deployment in the far term will increase the data rates even further. These technologies are: 1) optical links targeted for multi-Mbps rates, 2) 200W TWTA's, and 3) large, lightweight antenna structures.

The backbone data links will continue to require special techniques to operate at Earth-Mars distances with low SNR. Work is continuing, for near term implementation, on coding (Turbo codes) to increase the total amount of data passed during a transmission. These codes are used to recover data that would otherwise be lost due to noise and dropouts.

The link and network layer activities will focus on providing efficient error control through variants of Automatic Repeat Request (ARQ) tailored for the deep space links. In-space network store-and-forward technologies that enable data routing by address (not by command) must provide the translation between the protocols used on the long haul backbone link and the final proximity link. Definition of a standard network layer interface will facilitate integration of the long haul, local and on-board LAN would represent a significant achievement. In addition, a network management protocol tailored for deep space, but similar to the Internet's Simple Network Management Protocol (SNMP) will be required to configure and operate the backbone.

The backbone network will most likely support a variety of protocols for the higher layers. The transport and application layers may utilize variants of Internet-based protocols (e.g., TCP, UDP, FTP), near-Earth space protocols (e.g., SCPS-TP) or deep-space protocols such as the CCSDS File Delivery Protocol (CFDP) [5]. The trend is to use the protocols to enable data to be passed as a semantically meaningful package (such as a record in a file versus just a bit stream) to and between intermediate spacecraft en route to a science vehicle at the Mars end (in forward direction) or to Earth (in the return direction). In CFDP, the intermediate points provide a "custody" service, and assume responsibility for package delivery, removing the need for end-to-end acknowledgments over the links with long propagation delay. A second important feature of CFDP is to allow the delivery of partially complete packages, with the rationale that some precious data is better then none, as long as one is informed of the missing parts.

The application level services that may be implemented on top of the backbone in the far term will be directed toward creating an environment that can leverage from the state-of-the practice software engineering for terrestrial applications. Bringing Internet capabilities to the space backbone such as network servers to provide temporary storage, network switching, firewall protection, multicast services, email services, software control (XML, Java, Java Script, etc.) will be necessary for the implementation of autonomy in the operation of the network. Network access on-demand by user or vehicle will be important feature that will reduce the cost of network control and mission operations.

Technologies for proximity networks

Orbiter to/from Surface Interfaces– Mars surface vehicles may employ multiple RF subsystems. In the near term a proximity system that listens and radiates omni-directionally would be used for communication with relatively fast moving objects, such as a low altitude orbiter, for return of science data, video, or high-resolution images or for receiving lengthy software changes from Earth. This sub-system, perhaps UHF, may also be used for surface-to-surface proximity communications wherein a vehicle could coordinate its science data gathering with other nearby vehicle(s); and it could locate the other vehicle(s) using direction and ranging capabilities built into that system. A lower rate, directional antenna system would be employed as a backup link to Earth for transmitting and receiving short command strings and for sending back status telemetry and minimal science data. It would also be used in emergencies wherein the vehicle may send SOS messages to the Mars network or the Earth may attempt to regain command control of a malfunctioning vehicle. In later time frames, electronically steerable antennas may become feasible for both local and longer distance links.

The physical layer technologies needed for the proximity network elements that are used for communications between an orbiter and a surface vehicle are the small volume, mass, and power RF receivers and transmitters that utilize the UHF, X-band, and Ka-band frequency regimes. Antenna develop-

ment includes agile phased arrays, small steerable dishes, and omni-directional antennas. Also at the physical layer, the RF to digital interface developments include novel modem designs.

The use of focused antennas, Ka-band (20GHz-30GHz) receivers and transmitters is encouraged for vehicles that have moderate to large data files to transfer (100kB to multi-MB).

SiGe Radio Frequency Solid State Power Amplifiers (see Figure 6) are being developed at 8.4 GHz for orbiter to surface links. These amplifiers can be easily integrated with digital devices and circuit on Si substrate to reduce size of communication subsystem.

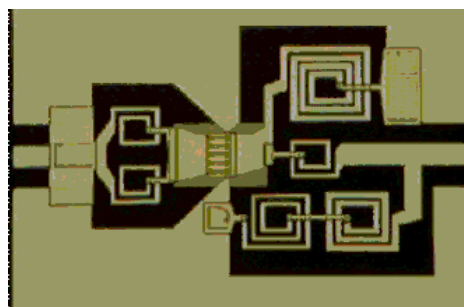**Figure 6.SiGe Solid State Power Amplifier**

Figure 7. MCAS Testbed

The Micro Communications and Avionics System (MCAS – Figure 7) for Mars orbit link has been developed. This is a multimission transceiver for low power and low mass missions. The transceiver has the following characteristics: Mass < 150g, Volume < 100 cm^3, Coherent BPSK (Manchester/NRZ, Supp/Resid), Convolutional coding (K=7, R=1/2), 0.5W Output power, and NF < 3dB, stability 10^{-6}. The next generation highly miniaturized system is under development.

The CCSDS Proximity-1 link layer protocol is presently being designed specifically for deep space surface-orbiter links [6] that are characterized by relatively short propagation times and relatively high SNR. Proximity-1 will be used in the near- and mid-term as the Mars protocol for the short-link portion of the surface-orbiter-Earth links. Proximity-1 allows the orbiter to access multiple, heterogeneous surface assets through a common hailing procedure. Once a session has been established between the orbiter and the surface element, the link can be moved to a set of working channels. Various types of communication services are accommodated such as the use of fixed block size or variable length messaging. The protocol provides a reliable message delivery service and a "best-effort" service. Some procedures are in place for handling contention from multiple orbiters; however, coordination methods are still being defined.

At the network layer, the data is either handed over to the backbone network where a simple relay function is required to accomplish the hop to Earth, or if the data is destined for another surface vehicle, it is handled by the proximity network layer. The technologies needed at the transport and application layers are similar to those discussed for the backbone network above, with shorter delays and greater need for energy and storage efficiency.
Mars Inter-spacecraft Networks – Most of the inter-spacecraft proximity networks will be implemented in multiple spacecraft systems that operate in a cooperative fashion, such as in constellations, formations, or clusters. These multiple spacecraft systems can be considered a single mission entity that might accomplish its scientific or infrastructure task by passing data between each other. Reasons for this inter-spacecraft communication may include coordination of relative alignment and positioning, distribution of computing tasks, master-slave or peer-to-peer cooperation, event timing and measurement triggering, and data passing in support of implementing a general communications network.

The physical layer technologies needed for the inter-spacecraft network elements are small volume, mass, and power RF receivers and transmitters that utilize the UHF, S-band, X-band, and Ka-band

frequency regimes. Antenna development includes agile phased arrays and omni directional antennas. Optical communications devices will eventually take part in inter-spacecraft networks. Also at the physical layer, further RF/optical to digital interfaces and modem advances are needed.

Another function of these communication physical layers will be the ability to measuring relative distances and attitudes between the spacecraft. The precision of these measurements will be dependent on the mission of the cooperative spacecraft. Coarse measurement will be satisfied by various RF system capabilities in range measurement. Fine measurement will be accomplished with the optical systems.

At the inter-spacecraft network's data link and network layers a peer-to-peer communication scheme is most appropriate. Modifications of Proximity-1 or emerging wireless LAN technologies (e.g., IEEE 802.11 [7] or Bluetooth [8]) are under consideration. These wireless LAN's will need asynchronous and real-time capabilities and will need to handle ad hoc joining and leaving for star-centered formations or more general multi-hop topologies. Also, motion dominated by predictable orbital mechanics may be incorporated in the link topology driven network adaptations.

The transport and application layers for the inter-spacecraft networks will use technologies similar to those used in the terrestrial Internet and for real-time applications on Earth. Additional development will be needed to implement network services to provide time synchronization and distributed computing coordination. In general, the autonomous coordination of the multi-spacecraft set will be accomplished at and above the inter-spacecraft network application layer, as in an agent-based architecture.

Mars surface networks– The Mars surface proximity networks are those wireless networks that are used to intercommunicate between the various entities in the Mars atmosphere or on the Mars surface. These proximity links are of somewhat lower data rate (multi-kilobits per second) than inter-spacecraft links (multi-megabits per second) and use different technologies. These networks are used to coordinate actions between Mars landers, rovers, aerobots, airplanes, etc. The surface proximity networks are also used to relay data from weak emitters to nearby, more capable data gatherers (such as intelligent landers or rovers) that can pass the data up the communications chain to Earth via their access network system.

Some example applications include:

1. Sensor webs for in-situ science – Small, low-cost, low-power nodes that provide sensors, multi-hop communications and on-board data processing using limited power supplies. These may be formed into arrays of randomly placed sensors that will self-organize to perform their sensing and communication functions. On-board processing is used to reduce the raw data by triggering on observed phenomena, performing local analysis and by combining results with neighboring sensors. These types of systems offer the unique ability to perform simultaneous multipoint measurement of a common phenomenon in order to a) derive a combined signal with higher SNR, b) correlate the various signals in order to localize an event or perform fusion, or c) "image" ("spatially pixelate") a region, such as seismic swarm characterization. Experiments designed to utilize these "network science" techniques are just beginning to emerge.

2. Rover collective. – Multiple rovers act as a coordinated unit to survey a region. Scout class (i.e., no DTE capability) elements maintain connectivity to base station via "bucket brigade" communication relay. This latter capability might also be achieved using stationary relay nodes that a rover drops off as it moves about (possibly picking them back up later).

3. Robotic outpost – Support interaction among a variety of robots and rovers to enable team-oriented operations such as support for interacting components of an in situ propellant production process.

4. HEDS outpost – Extension of the robotic outpost to more complex and demanding requirements. Also, an ad hoc network may be deployed as a supporting infrastructure that provides wireless connectivity (e.g., voice) and position tracking as humans (etc.) move about.

Surface ad hoc networks are currently under investigation for commercial, military and space applications. A combination of factors make the space environment unique with respect to the commercial and military applications and require additional research to realize these surface ad hoc networks for planetary exploration. The systems will need to be self-organizing and autonomous so that they can be automatically deployed and robust to faults imposed by the harsh environment. Overall cost is extremely dependent on the mass and size, greatly limiting the amount of energy or power generation capability that can be included. This drives the need for high-energy efficiency in the operational algorithms. Multihop networks that store and forward the information are useful from an energy efficiency point of view as well as help overcome line-of-site and long distance constraints. These networks need to adapt in order to squeeze out as much information as conditions permit; to send data even if holes occur in the file/stream, or perhaps even deliver data with errors as there might not be another chance to retransmit or collect the data. Most scenarios will benefit from a feed-forward of assets as much as possible, i.e., to build on previous mission assets as new in situ assets are overlaid. These will extend over very long time periods in comparison to commercial/military mission needs.

At the physical layer, the RF regime used is UHF, S-band, and X-band. Antennas are near omni-directional and are very small and lightweight. Very low power infrared may be included in the physical layer for very short distances. Very small, low mass and power integrated receivers, transmitters, and modems will be developed for at the physical layer of the surface proximity networks.

The surface proximity network's data link layers may use a variation of Proximity-1 that is peer-to-peer and modified for low energy use or they may be modeled after wireless LAN's such as Bluetooth or IEEE 802.11, but with modifications. The protocols will accommodate network dynamics such as faults, ad hoc-style handoff for mobile nodes, and cluster-based network routing and management. Many other protocol issues specific to sensor networks are currently under investigation in the research community. Energy efficiency in the link and network layers is important as well as geographic routing and data aggregation [9]. Most intelligent vehicle systems will likely provide proxy network services for the simpler more basic systems. Example services include temporary storage, data routing, multicast capability, time and operations synchronization, and network provisioning.

Technologies for On-board LAN

The various subsystems on-board the spacecraft are also following the general trend towards operating as a distributed system of autonomous but cooperating subsystems. The features/functions of the subsystems are increasingly implemented through software that is running on powerful processors embedded in the subsystems. The instrument and subsystem network interfaces to the on-board LAN physical layer are becoming increasingly complex and varied. Depending on the spacecraft complexity, there may be several types of local busses (e.g., IEEE 1394, Mil-Std 1553, Switched Ethernet, SpaceWire) that could be involved in information transfer. Further complications are arising from translating between the various protocols that must be supported.

In recognition of the growing problem, a new CCSDS activity concerned with Spacecraft On-board Interfaces (SOIF) has been established to define standard interfaces and a common reference model for future on-board LANS of unmanned spacecraft [10]. The standard will encompass many of the common on-board busses as well as the link, network, and transport protocols layers. Protocols that handle asynchronous data, isochronous data, real-time data and multicasting of data will be developed, tested and implemented. Gateway functions between the underlying protocols will be defined. The activity is expected to reduce development costs and risk for the spacecraft itself. Emergence of a common or standardized addressing scheme at the subsystem or instrument level will also reduce the complexity of the overall Mars communication architecture and move towards improving end-to-end interactions by Earth-based scientists and mission operators.

6. Conclusions

The Mars communication architecture has been described for implementation in the near-, mid-, and far-term. These architectures were based on current activities that are defining future Mars missions. The communication architectures have been decomposed into five elements: the backbone networks, three proximity networks (orbiter to/from surface, inter-spacecraft, and Mars surface networks), and the spacecraft on-board LAN's. These elements are then used to address the technologies required for the near to far-term architectures. Many of the technologies are already under definition and development in various research programs (e.g., [11]). These include microwave transmission devices and antennas, cryocooled receivers and MMIC's, high rate modem circuits, optical communication devices and systems, spacecraft/vehicle on-board LAN's, and data movement protocols.

The analysis also reveals the following technology gaps: 1) transparency to the application programs of the underlying communication protocols, 2) autonomous operation of the communication infrastructure, 3) efficient protocols for the inter-satellite and surface proximity links, 4) gateways based on common protocol standards and reference models between the architecture elements 5) high power microwave and optical sources, and 6) lightweight, large aperture antennas.

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